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PRODUCTION OF INCONEL 718 MORTAR TUBES BY HYDROSTATIC EXTRUSION

J. Richard Douglas, et al

Battelle Columbus Laboratories

Prepared for:

Watervliet Arsenal

July 1974

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Because of a desire to reduce the cost of producing mortar tubes from a nickel alloy (Inconel 718), hydrostatic extrusion was examined at Battelle, Columbus Laboratories. Using subscale tubes, extrusion parameters were developed and then applied to full size 60mm tubes. It was shown that tubes can be satisfactorily produced at a reduced cost. Estimates were developed to mass produce hydrostatically extruded tubes. The processing parameters, dimensional results and economic analysis are presented in detail.

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PRODUCTION OF INCONEL 718 MORTAR TUBES BY HYDROSTATIC EXTRUSION

PREPARED BY

J. R. DOUGLAS, G. E. MEYER
T. G. BYRER AND R. J. FIORENTINO
BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

PREPARED FOR

U.S. ARMY ARMAMENT COMMAND

BENET WEAPONS LABORATORY
WATERVLIET ARSENAL
WATERVLIET, N.Y. 12189

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FOREWORD

This program was conducted for the U. S. Army Watervliet Arsenal, Watervliet, New York, 12189, under Contract No. DAAF07-72-R-0082. The program was technically monitored for Watervliet Arsenal by Mr. Richard DeFries of Benet Research and Engineering Laboratories at Watervliet Arsenal.

The work described in this report was conducted by the Metalworking Division of Battelle's Columbus Laboratories by Mr. J. Richard Douglas, Project Engineer. Others contributing significantly to the program were: Mr. Warren R. Landis, Technician; Mr. George E. Meyer, Project Leader; Mr. Thomas G. Byrer, Associate Chief; and Mr. Robert J. Fiorentino, Chief, Metalworking Division. Dr. F. A. Simonen, of the Applied Mathematics and Mechanics Division also assisted in the program by reviewing the modifications to the container and by analyzing state of stress in the die.

The experimental data obtained in this program are contained in Battelle Laboratory Record Books Number 29855 and 29965.

TABLE OF CONTENTS

APPENDIX A

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES
(Continued)

INTRODUCTION

There has been continuing interest over the years in improving the service life of mortar tubes. Modified low-alloy steels have commonly been used for this application. These materials, however, have proven unacceptable in some cases, as the tubing has failed by bulging due to the excess heat generated during periods of sustained rates of firing. When the tubing is used in a less severe manner (where the tube is allowed to cool between firing), its life is acceptable although the tube eventually becomes unserviceable due to the erosion of tube ID.

Studies have been conducted[1,2] in which other materials have been examined for possible use in mortar tube applications. These materials have included high temperature nickel-base alloys and both low- and high-alloy tool steels. It was generally concluded from these studies that Inconel 718 alloy had the best combination of elevated-temperature tensile and yield strength, ductility, fatigue strength, and toughness at both -40 degrees and room temperature, based on mortar tube requirements. Thus, there has been considerable interest in use of this material for mortar tubes especially in those situations where sustained rates of firing are used.

However, this alloy has traditionally been expensive to fabricate into close-tolerance tubes. Two methods that have been used are to (1) machine the tube from solid bar stock or (2) machine a rough tube shell produced by conventional hot extrusion. Another possible approach is to reduce the rough tube shell down to the finished product by the numerous sequential steps normally involved in tube reducing or drawing. All of these methods are expensive to use, particularly where extensive machining is required, due to the poor machinability of this material.

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(1) DeFries, R. S., "An Evaluation of Elevated Temperature Materials for the 81mm Mortar Tube," Watervliet Arsenal Technical Report WVT-6629, Watervliet, N. Y., November 1966.

(2) DeFries, R. S., "An Evaluation of High Temperature Materials for Thin Walled Tubes," Watervliet Arsenal Technical Report WVT-7105, Watervliet, N. Y., May 1971.

It was felt that the hydrostatic extrusion process might offer an alternative lower cost method to producing high-quality Inconel 718 tubes as this technique can produce much larger reductions than are possible by conventional forming methods, and could eliminate much of the present machining requirements. In work done over the past 10 years at Battelle,(3,4,5) other laboratories in this country, including Watervliet Arsenal,(6,7) and around the world, the hydrostatic extrusion process shows great promise as a new technique for fabricating a variety of shaped and tubular products. Because fluid surrounds the billet in hydrostatic extrusion, friction between billet and container is virtually eliminated. This means it is practical to extrude long billets and produce such items as mortar tubes and other ordnance products of this type which have high length-to-diameter ratios. Work at Battelle has also shown that tubes can be extruded which have special external and internal configurations such as ribs, flutes, etc.

Since hydrostatic extrusion is typically a cold or warm deformation process, it has the inherent advantage of producing parts with good dimensional control, close tolerances, and fine surface finishes. Based on

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(3) Fiorentino, R. J., Richardson, B. D., Meyer, G. E., Sabroff, A. M., Boulger, F. W., "Development of the Manufacturing Capabilities of the Hydrostatic Extrusion Process", Technical Report AFML-TR-67-327, Air Force Contract No. AF33(615)1390, Battelle Memorial Institute, Columbus, Ohio, October, 1967.

(4) Richardson, B. D., Meyer. G. E., Uy, J. C., Fiorentino, R. J., Sabroff, A. M., "Prototype Production Process for Fabrication of Wire and Tubing by Hydrostatic Extrusion Drawing", Technical Report AFML-TR-70-82, Air Force Contract No. AF33615-68-C-1197, Battelle Memorial Institute, Columbus, Ohio, May, 1970.

(5) Gegel, G. A., et al., "A Manufacturing Method and Technology Study Covering Fabrication of Small-Diameter Missile Motor Cases", AMCMS Contract DAA-403-69-C-0472, Battelle Memorial Institute, Columbus, Ohio, February, 1971.

(6) Uy, J. C., Nolan, C. J., and Davidson, T. E., "The Hydrostatic Extrusion of Nickel-Base Superalloys at Room Temperature", Transactions Quarterly, Volume 60 No. 4, December, 1967.

(7) Nolan, C. J., and Davidson, T. E., "The Effects of Cold Reduction by Hydrostatic Fluid Extrusion on the Mechanical Properties of 18 Percent Nickel Maraging Steels", Transactions of the ASM, Vol. 62, 1969.

the potential advantages of hydrostatic extrusion for fabricating mortar tubes, this program was initiated to demonstrate the feasibility of extruding Inconel 718 to a configuration close to the current 60-mm mortar tube. It was expected that only the minimum of finishing and machining would be necessary to obtain the finished tube. Along with determining the process parameters, potential production costs were to be estimated to assess the economic feasibility of extruding mortar tubes by hydrostatic techniques on a production basis.

PROGRAM SUMMARY

Prior to starting the full-scale extrusion studies on Inconel 718 tubes, a series of subscale trials were conducted to establish the process parameters and resolve a possible problem that frequently occurs in the cold extrusion of tubes; namely, the occurrence of ID defects during extrusion. Subscale trials conducted in this program established satisfactory extrusion parameters and showed that if an ID reduction of at least 10 percent was taken during the course of extrusion, high-quality ID surfaces could be achieved. Thus, these results were taken into account when designing tooling and carrying out the full-scale trials.

The feasibility of producing Inconel 718 mortar tubes by hydrostatic extrusion was established in this program. The mortar tube extrusions produced in this study are shown in Figure 1 along with several steel extrusions produced to check out tooling and process parameters.

These tubes were of excellent quality as evidenced by the as-extruded dimensions listed below for a lot of four tubes:

Outside Diameter	-	2.785 ± 0.002 inches
Inside Diameter	-	2.362 ± 0.008 inches
Wall Thickness	-	0.209 ± 0.014 inches
Concentricity	-	0,014 inches maximum .

Cost estimates were made for producing the mortar tubes in quantities from 100 to 5000. These estimates, based on starting with a hot

FIGURE 1. EXTRUDED INCONEL 718 AND STEEL MORTAR TUBES MADE BY HYDROSTATIC EXTRUSION TECHNIQUES IN BATTELLE'S 2500-TON HYDRAULIC PRESS

extruded tube as a tube blank and making the finish mortar tube by hydrostatic extrusion, are summarized below:

Quantity	Cost per Tube, Dollars
100	514
500	384
1000	372
5000	353

A major component in these estimated costs is that of the hot extruded tube blank. If the cost of the starting tube preform can be reduced, it would significantly affect the overall cost to produce each tube. Preliminary analysis indicates that if a thick wall, short tube preform could be produced by back extrusion of a solid billet, the overall tube costs could be further reduced by about another 25 percent allowing for a double hydrostatic extrusion step to make the mortar tube.

In view of the potential cost savings that could be achieved by utilizing back extruded preforms, it is recommended that further studies being conducted which would develop this technique and establish the parameters for hydrostatic extrusion starting with back extruded preforms. Recommendations have also been included for examining two other potential approaches to improving mortar tube manufacturing methods and reducing tube production costs. One of these is a front augmented extrusion technique which potentially reduces fluid pressure requirements for extrusion and eliminates the need for removing the ID taper which is produced by present techniques. A second approach would involve the use of warm hydrostatic extrusion techniques to enable higher extrusion ratios to be achieved while still maintaining the high-quality surface and dimensional control demonstrated in this program.

The success of this program opens the door to applying similar hydrostatic extrusion techniques to a wide variety of ordnance products. Thus, consideration should be given also to investigating the applicability of this process to other types of products in the Army's arsenal which could benefit from the potential process improvements and cost reductions indicated here.

PROGRAM OBJECTIVES AND GENERAL APPROACH

The objective of this proposed program was to develop cold hydrostatic extrusion techniques to manufacture 60-mm mortar tubes, 2.764-inch OD x 2.390-inch ID x 38 inches long from Inconel 718 alloy. Fabrication of these tubes was expected to be done in two steps. The first was to be a hydrostatic extrusion operation in which the bulk of the reduction on the tube is made. In the second processing step, the tube was to be heat treated, sized to the final dimensions, and straightened as required. After processing, the finished tubes were to be dimensionally checked and inspected at Battelle, and selected tubes sent to Watervliet Arsenal for more extensive evaluation.

With processing steps defined, a cost study was to be made to permit cost estimates for producing these tubes in quantities up to 5000 units. These data, along with detailed descriptions of the work conducted on this program, are included in this final report.

PROCESSING OF TUBING

Prior to fabricating the needed tooling to extrude the full-size mortar tubes in our 2500-ton hydraulic press, it was decided to conduct some subscale trials in our 700-ton hydraulic press. These limited subscale trials were conducted, and based on the results of this work, tooling designs and process parameters were selected for fabrication of full-size tubes. Both series of extruded trials are discussed below.

Subscale Trials

A series of subscale trials on both carbon steel and Inconel 718 materials was conducted to define process parameters and explore potential tube ID defect problems which had been periodically encountered in the hydrostatic extrusion of certain high-strength materials. It was felt that similar ID problems could be encountered in this program in the extrusion of full-size tubes. It was desired to resolve these questions before the full-scale studies were undertaken.

Defects have been detected on the inside surface of some hydrostatically extruded tubing fabricated on previous government and industry-sponsored research programs. These defects, which may appear as cracks or roughened areas, are in the transverse direction and are commonly aligned with ID machining marks from the starting billet. The cause of the defects is not precisely known but is felt to be related to the state of stress on the inside surface during extrusion.

In the ironing approach to tube-making where the billet ID is the same as the extruded tube ID, the inside surface fibers of the tubing are elongated in the axial direction with little circumferential movement. Thus, these inside fibers deform in a largely tensile manner and it is suspected that the defects are a result of a lack of stability in this direction (perhaps a phenomena similar to necking).

An examination of literature indicated that other investigators had encountered similar types of problems. In one particular case, Cruden[8] encountered these problems in conventional cold extrusion of tubing. He found two methods of solving this problem to be successful and both were explored in this program. These involved (1) significantly reducing the inside diameter during extrusion and (2) extruding the material through dies whose entry angles are relatively small in comparison to die angles normally used.

In the work conducted in this program, these same two approaches were tried and it was generally found that the defect problem persisted regardless of the die half-angles evaluated (22-1/2, 15, and 10 degrees), but a very definite improvement was encountered when 10 and 20 percent ID reductions were taken. One tube produced during these trials is shown in Figure 2 and has an excellent surface finish of about 4 to 7 microinches, rms. Thus, it appeared that the potential problem of ID defects could be solved by reducing the billet ID by as little as 10 percent during the extrusion process, and tooling designs and billet dimensions for the full-scale efforts were modified accordingly.

In addition to defining conditions for producing good ID surfaces, these trials established that:

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(8) Cruden, A. K., "The Effect on the Extrusion of Steel of a Prior Extrusion Operation", NEL Report No. 321, East Kilbride, Glasgow: National Engineering Laboratory, January, 1968.

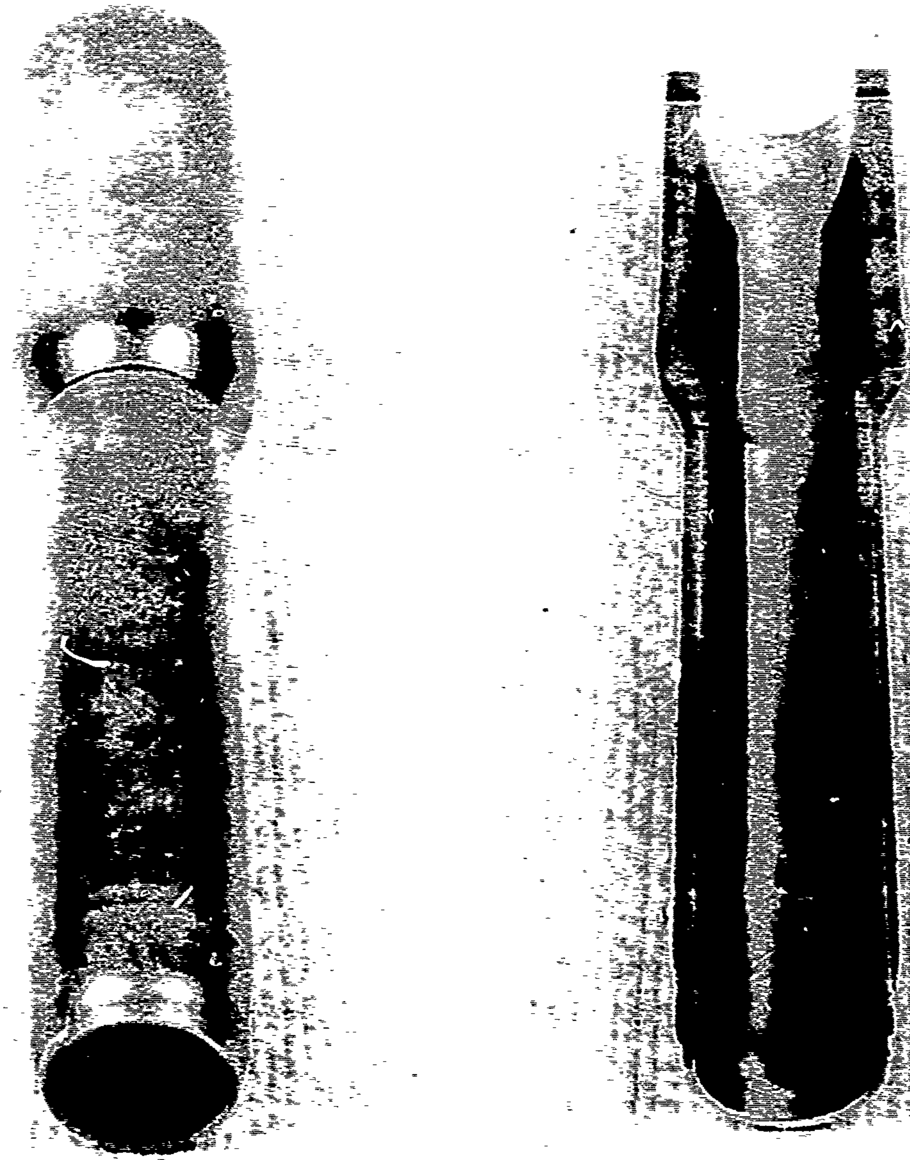

FIGURE 2. SUBSCALE INCONEL ALLOY 718 TUBE EXTRUDED IN THIS PROGRAM SHOWING EXCELLENT ID SURFACE FINISH DUE TO INCORPORATING AN ID REDUCTION DURING EXTRUSION

(1) Extrusion ratios up to about 2.5:1 are possible with Inconel 718 at room temperature at fluid pressures up to 250,000 psi

(2) Die angle of 22-1/2 degree semiangle is satisfactory and no significant benefits were obtained by using angles as small as 10 degrees

(3) Copper plating of Inconel 718 billets in combination with resin-bonded graphite-MoS_2 coatings would be used as the lubrication system in the full-scale studies.

(4) Ram speeds in the range of 6 ipm to 20 ipm were satisfactory.

Also included in the subscale work was an evaluation of other modifications in tube-making techniques including a concept involving "product-augmented extrusion" where an augmenting or additional force is applied to the extruding product.

This approach offers several potential advantages including reduced fluid pressure requirements. More details on this technique are reported in Appendix A.

Full-Scale Extrusion Trials

The extrusion trials for producing the full-size mortar tubes were conducted in hydrostatic extrusion tooling which was designed and constructed at Battelle. The container, shown in Figure 1, is of a 5-ring design and has a basic bore size 7 inches in diameter x 30 inches long.

For this program, the bore diameter was reduced to 3.500 inches using a two-ring insert assembly. The outer ring has a straight OD and tapered ID. Conditions were reversed for the inner ring. These matching tapered surfaces were made with an interference fit so that when the smaller ring is pressed into position in the larger ring, a prestress is achieved on the inner ring so that the entire assembly can withstand the high extrusion pressures. This system was designed for use at pressures up to 250,000 psi and the tooling was installed in our 2500-ton vertical hydraulic press. The container was manipulated in a vertical manner using two independent cylinders positioned below the press which have a total hold-down capacity of 400 tons.

Figure 3 illustrates the mandrel, billet, and die arrangement used in these trials. The ram acted directly on the top surface of the mandrel and transmits the force to pressurize the fluid in this manner. As can be seen in the figure, seals are placed at the bottom of the flanged part of the mandrel and, therefore, pressurization occurs only below this point.

The load applied by the ram was measured and plotted as a function of ram travel on a Hewlett Packard X-Y recorder and data recorded in the form of a plot of pressure-versus-stroke. Typical of these plots is shown in Figure 4 for both Inconel 718 and the AISI 1018 steel (used as a billet material to check out tooling) extruded in this program.

The dies used in these trials were specially designed to be press-fit on the tapered liner surface as shown in Figure 3. These dies were prestressed in much the same manner as the inside ring of the hydrostatic extrusion container. Lead metal was plated on the OD surface of the dies to assist in lubricating the dies during seating and to act as a seal against fluid leakage between the outside surface of the die and matching tapered surface on the container.

For both Inconel 718 and AISI 1018 steel, the billets measured 3.450 inch OD by 2.650 inch ID, and were extruded to nominal dimensions of 2.800 inch OD x 2.350 inch ID. Because the mandrel was tapered (0.0015 inch per inch of length), the ID of the tubing was also slightly tapered.

Procedure

For each trial, the copper-plated billet was sprayed with Fel-Pro C (a molybdenum-sulfide-graphite lubricant) and then coated with castor oil. The die was positioned in the container and prestressed by engaging the container hold-down to a load of 400 tons. The billet was then placed inside the container so that the nose end rested against the die. The billet nose had previously been reduced in diameter so that a seal could be achieved between the billet ID and the mandrel. Fluid was then added to the inside of the billet and retained by simply capping the billet nose end. The mandrel was then inserted into the container so that the end sealed the nose of the tube against fluid leakage.

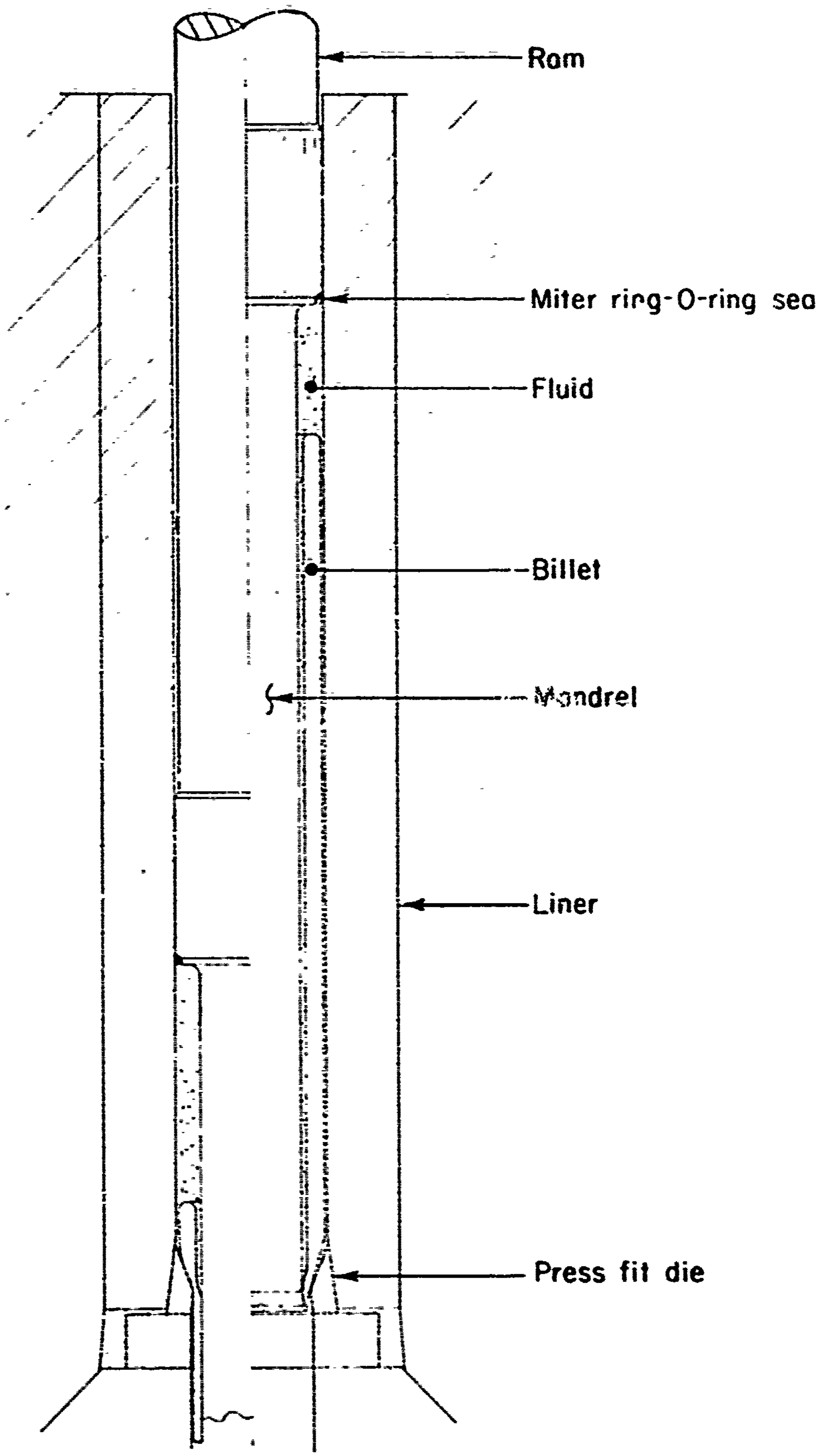

FIGURE 3. SPLIT-VIEW OF TOOLING ARRANGEMENT USED FOR EXTRUDING THE INCONEL 718 MORTAR TUBES

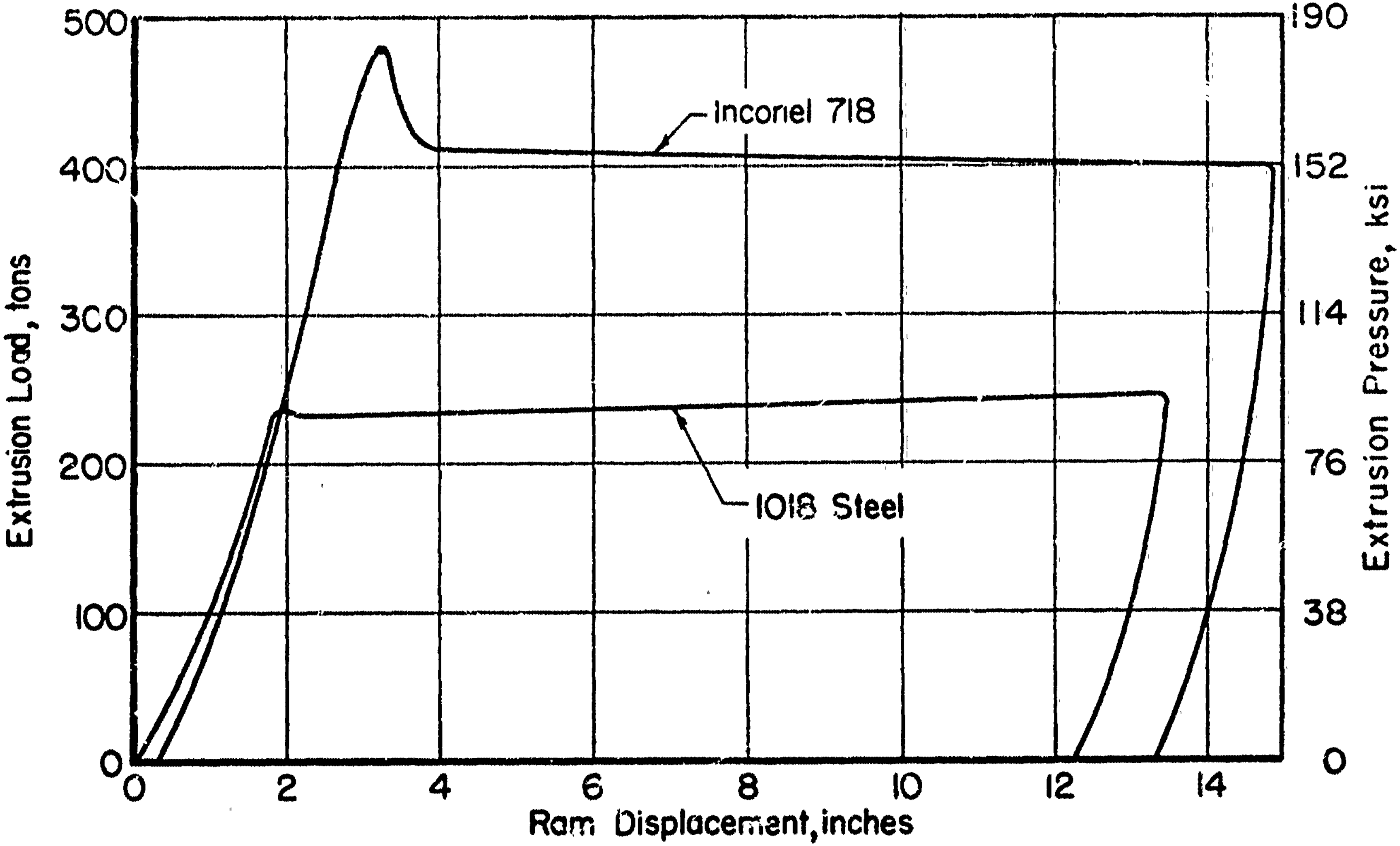

FIGURE 4. TYPICAL LOAD-DISPLACEMENT PLOT FOR EXTRUDING THE INCONEL 718 AND AISI 1018 STEEL TUBES

The condition utilized in the extrusion of the full size Inconel 718 and steel tubes were similar for all of the trials. These conditions are listed below:

Fluid	-	Castor Oil
Lubrication	-	Copper plate + resin-bonded graphite MoS_2 coating
Billet Dimensions	-	3.450 in. OD x 2.650 in. ID x 20.0 in. length
Tube Dimensions (Nominal)	-	2.787 in. OD x 2.363 in. ID x approximately 40 in. length

Extrusion Ratio

Inconel 718	-	2.2:1
Steel	-	2.4:1

Extrusion Pressures

Inconel (718)	Breakthrough	-	180,000 - 195,000 psi
	Runout	-	150,000 - 155,000 psi
Steel	Breakthrough	-	82,000 - 90,000 psi
	Runout	-	76,000 - 82,000 psi

Die Configuration

Diameter	-	2.765 (estimated prestressed diameter)
Approach Angle	-	22-1/2° (half angle)
Land Length	-	0.2 inch

Press Ram Speed	-	Approximately 5 ipm
Mandrel Configuration	-	2.390 inches tapering to 2.356 inches over 22 inches of length (0.0015 in/in).

The extrusion trials were completed without complication and indications were that litt'e or no postextrusion processing of these tubes would be required. Thus, the extruded Inconel 718 tubes were straightened, heat treated (1150 F/8 hr.) and subsequently ID honed to finish the tube fabrication.

EVALUATION OF EXTRUDED TUBES

The tubing produced in this program was examined for dimensional accuracy. Results are shown in Table 1 and summarized below for Inconel 718.

	Variation, inches
Outside Diameter	2.783 to 2.787
Inside Diameter	2.354 to 2.370
Concentricity (difference between OD and ID centers)	0.008 (typical) 0.014 (maximum)

The ID variation is due in part to the effects of the tapered mandrel and to the eccentricity measured in the tube. Concentricity at the nose end was quite good but lessened as extrusion progressed. It is not clear why the Inconel 718 tubes showed less concentricity over the tube length but this could occur as a result of variations in lubricant behavior and metal flow through the die. The Inconel tubes were also found to have the ID defects described earlier in this Report in spite of the reduction taken on the inside diameter.

After dimensional checks were made which showed the tubes to be within the required tolerances of the "modified specification", four tubes were honed on the ID surface only and shipped to the Sponsor for its upcoming evaluation studies.

COST EVALUATION

A cost study on producing Inconel 718 tubing for mortar tubes by hydrostatic extrusion have been made and is reported in Table 2. This estimate of costs was made for producing 100, 500, 1000, and 5000 extrusions utilizing several assumptions made necessary because production facilities for hydrostatic extrusion of this type of tubing do not currently exist in the United States. These assumptions were:

(1) A reduction in area of 60 percent (2.5:1) would be obtained in a single cold hydrostatic extrusion step

(2) Only one extrusion operation will be required to reduce the billet to the tube size desired

TABLE 1. DIMENSIONS AND CONCENTRICITY OF SELECTED BILLETS AND AS-EXTRUDED TUBES

All Values in Inches

Trial Number	Material	Form	Dimensions of Extruded Tubes, inches: OD Nose	OD Butt	ID Nose	ID Butt	Concentricity(1) Nose	Concentricity(1) Butt	Straightness(2) As-Extruded	Straightness(2) After Straightening
9	Inconel 718	Billet	3.448	3.449	2.649-2.650	2.648	0.000	0.000	-	-
		Extrusion	2.786	2.787	2.356	2.363	0.001	0.008	0.040	0.006
10	Inconel 718	Billet	3.445	3.445	2.650	2.651	0.000	0.000	-	-
		Extrusion	2.787	2.787	2.355	2.366	0.000	0.006	0.049	0.008
11	Inconel 718	Billet	3.448	3.447	2.645	2.645	0.000	0.000	-	-
		Extrusion	2.785-2.786	2.783-2.784	2.356	2.783-2.784	0.001	0.006	0.058	0.010
12	Inconel 718	Billet	3.446	3.445	2.649	2.650	0.000	0.000	-	-
		Extrusion	2.787	2.786	2.359	2.368	0.000	0.006	0.046	0.011
14	Inconel 718	Billet	3.447-3.448	3.445	2.649	2.644-2.645	0.000	0.009	-	-
		Extrusion	2.786	2.787	2.354	2.370	0.002	0.014	0.073	0.013
2	AISI 1018 Steel	Billet	3.447	3.449-3.450	2.624-2.625	2.623-2.624	0.000	0.000	-	-
		Extrusion	2.767	2.767	2.352-2.353	2.369-2.370	0.001	0.000	0.018	-

(1) Concentricity measurements shown are based on dimensional difference between the center of the OD and the center of the ID. $(OD_{max} - ID_{min}) \div 2$

(2) Straightness measurement is based on the maximum deviation of the tube center line from a truly straight line.

TABLE 2. ESTIMATED COST FOR MANUFACTURE OF INCONEL ALLOY 718 MORTAR TUBES BY HYDROSTATIC EXTRUSION

Operation		Cost Per Part, dollars			
General	Specific	100	500	1000	5000
Billet Preparation	Hot Extruded Tube(1)	408.56	298.56	290.70	277.62
Billet Preparation	Bore ID(2)	5.97	5.73	5.64	5.48
Billet Preparation	Turn OD(2)	8.96	8.70	8.63	8.46
Billet Preparation	Copper Plate(1)	12.00	9.50	9.50	9.50
Hydrostatic Extrusion	Extrusion Costs(3)	15.78	8.03	7.20	6.30
Postextrusion Processing	Cleaning(3)	0.72	0.72	0.72	0.72
Postextrusion Processing	Straightening(4)	3.75	3.75	3.75	3.75
	Heat-Treating(3)	4.26	2.53	2.03	1.20
	Grind OD(5)	15.80	13.90	13.27	12.04
Postextrusion Processing	Hone ID(5)	33.33	29.20	27.90	25.30
Postextrusion Processing	Cut to Length(4)	5.00	3.50	3.50	3.00
		514.13	384.12	372.84	353.37

(1) Estimate from commercial supplier

(2) Calculations based on metal removal rates and cost studies conducted in other Battelle programs(4,5)

(3) Calculated based on cost studies conducted in other Battelle programs(4,5)

(4) Estimate based on time required for identical operation in this program

(5) Estimate based on cost of this operation in this program.

(4) Richardson, B. D., Meyer, G. E., Uy, J. C., Fiorentino, R. J., Sabroff, A. M., "Prototype Production Process for Fabrication of Wire and Tubing by Hydrostatic Extrusion Drawing", Technical Report AFML-TR-70-82, Air Force Contract No. AF33615-68-C-1197, Battelle Memorial Institute, Columbus, Ohio, May, 1970.

(5) Gegel, G. A., et al., "A Manufacturing Method and Technology Study Covering Fabrication of Small-Diameter Missile Motor Cases", AMCMS Contract DAA-H03-69-C-0472, Battelle Memorial Institute, Columbus, Ohio, February, 1971.

(3) Die life will be 25,000 parts or better

(4) The minimum extrusion container life will be 10^5 extrusions

(5) A production rate of 15 parts per hour can be attained.

The costs were based on the best available information and quotations were obtained where possible. It was also assumed that the process was optimized to extrude close to finish dimensions thereby minimizing the finishing operations.

In some portions of the cost estimates, a learning curve effect has been applied which allows for greater efficiency in production of larger quantities. Basically, a worker or group of workers learn as the several steps of an operation is repeated thereby permitting a decline in the direct labor input per unit.

These results generally show that for a production lot of 500 or more, production costs would be on the order of $350 to $400 per finish tube. Examination of these costs shows that the single large component of cost is the starting billet. This cost is based on purchase of a hot-extruded tube blank which weighs about 28 pounds (a per pound cost of $10 to $14.50 for material and extrusion). It is our opinion that this tube blank could be produced at a much lower cost. Assuming a base metal price of $4.50/pound, it should be possible to fabricate a starting billet by back extrusion of a solid round to form a cup at a total price of about $6 per pound. For a 28 pound billet, this would make the starting tube shell cost about $170.

Assuming now that <u>two</u> hydrostatic extrusion steps are required, since the back extruded cup will likely be thicker walled and shorter than a hot-extruded tube, to make the finish tube, costs for 500 tubes might be as follows:

Back-Extruded Preform	$170	
Machine OD, ID, and Copper Plate	24	(Table 3)
Two Extrusion Steps	16	(Table 3)
Intermediate Anneal and Other Preparations	24	(Table 3)
Post-Extrusion Processing	54	(Table 3)
TOTAL	$288	

Thus, the cost per mortar tube could conceivably be reduced from $385 (Table 2) to $288-- a 25 percent reduction.

SPECIFICATIONS OF FINISHED TUBES

(All Values in Inches)

Tube No.	Outside Diameter	Inside Diameter	Wall
1	2.760/2.762	2.363	.199/.201
		2.369	.185/.206
2	2.782/2.785	2.360	.210/.213
		2.367	.204/.214
3	2.782/2.785	2.364	.208/.210
		2.367	.203/.216
4	2.781/2.782	2.358	.210/.213
		2.367	.202/.212

The two values given for the tube ID represent measurements on opposite ends of the tube and reflect residual ID taper after honing. Wall variations at opposite ends of the tube are also reported.

RECOMMENDATIONS FOR FUTURE WORK

The feasibility of extruding Inconel 718 mortar tubes by hydrostatic extrusion has been demonstrated by the results of this program. In addition, a cost study would suggest that tubes could be fabricated by this method at significant cost savings over techniques now being used. Obviously, however, in the limited work done here, there still remains further process optimization that could be undertaken to refine the extrusion techniques and better establish reliable per-part production costs. Several of these techniques are described below.

First, consideration should be given to conducting further extrusion trials utilizing much of the existing tooling but starting with a back-extruded preform. As the cost estimates have indicated, a significant reduction in starting billet costs could be realized by using a back extruded cup. Thus, experimental studies should be undertaken to develop necessary process conditions for utilizing this type of starting billet.

One particularly attractive alternative that has been given a brief examination in this program is that of product-augmented extrusion. This approach appeared to be particularly interesting because the required fluid pressures are small and tubing is produced without a taper on the inside diameter. The Appendix to this report elaborates on this process and indicates the potential for this approach.

A third approach to be considered would involve utilization of warm temperatures to achieve even higher extrusion ratios. Although Inconel 718 is considered a high-strength material at elevated temperatures, it should be possible to utilize extrusion temperatures on the order of 1500 F to reduce the flow stress and achieve extrusion ratios higher than the 2.2:1 ratio utilized in this program. Potentially, fluid and lubrication systems could be worked out for these temperatures so that perhaps the two-stage extrusion step mentioned earlier in conjunction with use of the back extruded preform could again be reduced to only one extrusion step.

Thus, several approaches appear attractive to further define the use of hydrostatic extrusion techniques in mortar tube manufacture. Once the tubes produced on this program have been satisfactorily evaluated by Watervliet Arsenal, it would be opportune to discuss these various approaches to implementing one or more of these methods in more detail.

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APPENDIX A

COMPARISON OF FRONT-AUGMENTED AND BACK-AUGMENTED EXTRUSION

It was decided in the subscale trials to explore the possibility of an augmented approach to hydrostatic extrusion. This approach offers several advantages, the major one being a greatly reduced fluid pressure. Reduced fluid pressure requirements can mean that higher reductions can be taken for a given available press tonnage.

This augmentation may take one of two forms. It may be possible to augment the extrusion by an additional force acting either directly on the billet, or on the extrusion product. For simplicity, these may be referred to as "billet-augmented extrusion" and "product-augmented extrusion", respectively. Figure A-1 illustrates the two approaches as they were considered in this program. As can be seen in Figure A-1, the source of the augmentation force is the fluid in both cases. The magnitude of the augmenting force is equal to

$$F = A_m P_f \quad ,$$

where

F = the augmenting force

A_m = cross sectional area of the mandrel

P_f = fluid pressure.

In billet-augmented extrusion, the force is applied to the billet and stress on the billet due to the augmenting force is

$$\sigma_B = \frac{A_m P_f}{A_B} = \frac{A_m P_f}{R A_P} \quad ,$$

where

σ_B = augmenting stress on the billet

A_B = cross-sectional area of the billet

A_P = cross-sectional area of the extruded product

R = extrusion ratio.

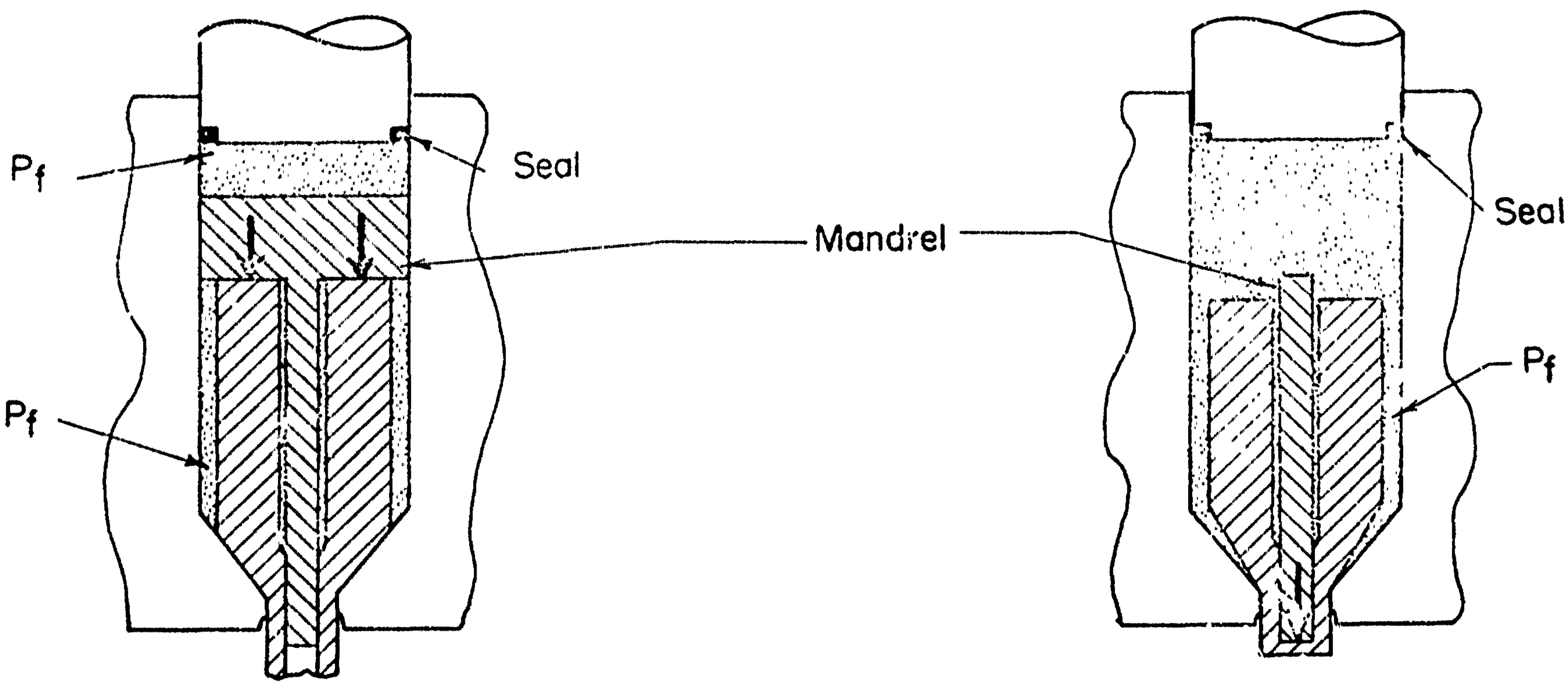

FIGURE A-1. TWO APPROACHES TO AUGMENTED HYDROSTATIC EXTRUSION EXPLORED IN THE SUBSCALE TRIALS IN THIS PROGRAM

Obviously, extrusion by this method is limited by the stress that can be placed on the billet without causing it to upset. Since the fluid pressure itself will not contribute to upsetting, it is necessary to examine only the stress due to the augmenting force, σ_B.

In one form of product-augmented extrusion, the force is applied to the extrusion product only and the stress on the extrusion product is

$$\sigma_P = \frac{A_m P_f}{A_P} = \frac{RA_m P_f}{A_B} \quad .$$

In this case, the extrusion is limited by the stress that can be placed on the extrusion product without failure or $\sigma_P \leq$ yield strength of the product.

To compare the two approaches, it is approximately correct to say that the extrusion pressure for a given reduction on a given material is constant and is equal to the fluid pressure plus the augmenting stress.

$$P_E = P_{f1} + \sigma_B$$

or

$$P_E = P_{f2} + \sigma_P \quad ,$$

where

P_E = extrusion pressure

P_{f1} = fluid pressure for billet-augmented extrusion

P_{f2} = fluid pressure for product-augmented extrusion.

Thus,

$$P_{f1} + \sigma_B = P_{f2} + \sigma_P$$

or

$$P_{f1} + \frac{A_m P_{f1}}{A_B} = P_{f2} + \frac{RA_m P_{f2}}{A_B}$$

$$P_{f1} \left(1 + \frac{A_m}{A_B}\right) = P_{f2} \left(1 + \frac{RA_m}{A_B}\right)$$

and

$$\frac{P_{f2}}{P_{f1}} = \frac{\left(1 + \frac{A_m}{A_B}\right)}{\left(1 + \frac{RA_m}{A_B}\right)} .$$

Thus, the fluid pressure for product-augmented extrusion can be smaller than that for billet-augmented extrusion by a ratio of

$$\frac{1 + \frac{A_m}{A_B}}{1 + \frac{RA_m}{A_B}} .$$

Generally it could be concluded from these trials that augmented extrusion is applicable only if the stress due to the augmentation force will not exceed the yield stress of the member to which the load is applied. Specifically, it means that in product-augmented extrusion, the augmenting stress should not exceed the tensile yield strength of the extruded product. In back-augmented extrusion, the augmenting load should not exceed compressive yield strength of the billet material. When these limits are exceeded, the effect is fairly obvious. On the one hand, the extrusion products may be elongated and rupture. In the other instance, the billet may upset and thereby increase the extrusion ratio causing even higher required extrusion pressures.

In the subscale trials conducted in this program, it was determined that billet-augmented extrusion would not be possible. The required extrusion pressures would generate an augmenting stress that would have exceeded the yield strength of the billet. In product-augmented extrusion, the conclusion was not quite as clear. It appeared that the extrusion might be marginally possible by this technique; however, because this was not known with certainty, this approach was not followed in the subsequent full-scale trials. As recommended elsewhere, this method should be considered further, as, in both cases, the extrusion pressures were substantially reduced from what is required by unaugmented extrusion.

As an example, one can compare the fluid pressures that would be required to extrude the full-size mortar tubes by conventional hydrostatic extrusion; by product-augmented hydrostatic extrusion, and by billet-augmented hydrostatic extrusion. If the extrusion pressure for conventional hydrostatic extrusion is 155,000 psi (as it was found to be in this program) for a 2.22:1 reduction, the area of the mandrel is 4.36 sq. in, and the area of the billet is 3.84 sq. in. The following calculations can be made:

$$P_E = P_{f1} + c_B$$

$$= P_{f1} + \frac{P_{f1}A_m}{A_B}$$

$$= P_{f1}\left(1 + \frac{A_m}{A_B}\right)$$

$$P_{f1} = \frac{P_E}{\left(1 + \frac{A_m}{A_B}\right)} = \frac{155{,}000}{1 + \frac{4.36}{3.84}} = \frac{155{,}000}{2.135}$$

$= 73{,}000$ psi for product-augmented extrusion

$$P_{f2} = P_{f1}\left(\frac{1 + A_m/A_B}{1 + RA_m/A_B}\right)$$

$$= 73{,}000\left(\frac{2.135}{1 + 2.222\ (1.135)}\right)$$

$$= 73{,}000\left(\frac{2.135}{3.52}\right) = 44{,}000$$ psi for billet-augmented extrusion.

Thus, the extrusion pressure equals

155,000 psi for conventional hydrostatic extrusion
73,000 psi for billet-augmented extrusion and
44,000 psi for product-augmented extrusion.